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Rubens flame-tube demonstration

George W. Ficken and Francis C. Stephenson

The scenario is this: You and/or your students decided to construct a flame-tube demonstration of standing sound waves. It works beautifully, as shown in Fig. 1 under “normal operation,” with the flame maxima appearing at the pressure “nodes” (N’s). [It should be noted that the pressure antinodes (AN’s) are located at the displacement nodes and the pressure N’s at the displacement antinodes, but we shall always be referring to pressure N’s and AN’s.] Having finished, but with the sound still on, you quickly turn off the gas, but groups of tiny blue flames persist at regular intervals along the tube for about three minutes! An observant student then notices that the remaining blue flames cluster around the AN’s, rather than the N’s, where previously the flames were largest.1 You repeat the test, with the same results. He wants an explanation!

Having none, you try turning the sound off first, and this time (of course!) the flames all go out immediately. Next, you leave the sound on and very slowly decrease the gas flow, noting that the large flames at the N’s decrease in size more rapidly than do the smaller ones at the AN’s, eventually themselves becoming the smaller ones. This condition is shown in Fig. 2, and we call it a “reversal.” These flames at the N’s, now smaller, are the first to go out as gas flow is decreased.

You consult every reference your library has available and still come up empty; this in spite of the fact that for almost a century there has been interest in the Rubens flame-tube demonstration, recently discussed in The Physics Teacher.2,3,4 Attempts to explain this phenomenon have been complicated by the fact that under certain more extreme conditions, the flames exhibit a “reversal.” Rubens and Krigar-Menzel5 theorized qualitatively that the phenomenon was caused by the viscosity of the gas. They stated that due to viscosity eddies were formed near the tube wall and somehow helped push gas out through the holes. Our explanation does not rely on the gas having viscosity, and, in fact, our measurements indicate that viscosity effects are very small. However, these authors obviously did a great deal of pioneering experimental and theoretical work on this demonstration, and it is surprising that subsequent classroom demonstrators did not extend their work using more modern instruments. We did get some ideas from them, but had trouble correlating much of their work with ours, and developed our own methods of investigation, both experimental and theoretical.

George Ficken received his B.A. at the University of Connecticut and M.S. at Michigan State University. His teaching experience includes one year each at a prep school and a two year college, and eight years at Fenn College, which became Cleveland State University in 1965. His research is always related to teaching, the latter including general physics, nuclear radiation detection, and introductory astronomy. (Cleveland State University, Cleveland, Ohio 44115)

Francis C. Stephenson received his M.A. and Ph.D. at the University of Toronto. Prior to his present position as associate professor of physics he was employed as a research physicist at General Electric for twelve years. His research interests include vibration and gas discharge. (Cleveland State University, Cleveland, Ohio 44115)
Rossing hints that second-order effects give time-average pressures leading to a reversal. With the conditions of our experiment, the difference in time-average pressure between N’s and AN’s due to second-order effects is too small by several orders of magnitude to produce an appreciable flame modulation. He uses the equation

\[ \langle P \rangle = P_o - \rho_o (u_o/2)^2 \sin^2 \left( \frac{\pi x}{L} \right) \]

to give the time-average pressure at points along the axis of the tube, where:

- \( P_o \) is the static pressure within the flame tube, very close to 1 atm = 10^5 N/m^2 in any experimental setup;
- \( \rho_o \) is the gas density within the tube, about 0.6 kg/m^3 (at 55°C);
- \( u_o \) is the maximum particle velocity (obtained by calculation from the measured sound levels under normal operation at the pressure antinodes inside the tube), approximately 0.08 m/s.

Inserting these values into his equation gives us a correction term of only 10 x 10^4 N/m^2, small compared to our measured static gauge pressure of roughly 1N/m^2 (which expels the gas from the flame tube).

Our approach was to apply the Bernoulli equation to the gas flow out through a hole of the flame tube:

\[ P_{in} = P_{out} + \frac{1}{2} \rho v^2 \]  
\[ P_{in} - P_{out} = P_{gauge} + P_m \sin \omega t = \frac{1}{2} \rho v^2 \]  
\[ v = \sqrt{(p_g + p_m \sin \omega t)/2 \rho} \]  
\[ F = \rho A v = A \sqrt{(p_g + p_m \sin \omega t)/2 \rho} \]

where \( P_{in} \) is the absolute pressure of the gas inside the tube and far from the hole being considered;

- \( P_{out} \) is the absolute pressure of the gas at a point in the gas stream just outside the hole, taken to be 1 ATM;
- \( v \) is the speed of the gas through the hole;
- \( \rho \) is the gas density at about 75°C (i.e., 0.56 kg/m^3), near a hole;
- \( \omega \) is the angular frequency of the sound wave;

\( p_m \) is the sound pressure amplitude;

\( F \) is the mass flow rate;

\( A \) is the effective hole area.

From Eq. (4) we can see that the mass flow rate is proportional to the square root of the excess pressure. This means that for a given change in pressure, the velocity is affected less at high pressure than at low pressure. As a result, the increase of gas flow outward during the positive swing of the cycle (high pressure) is not as great as the decrease of gas flow during the negative swing. This results in a decrease in net flow outward through the holes at the instant when the sound is turned on. This impeding effect produced by the sound is obviously most pronounced at the AN’s and least at the N’s. Therefore, the net gas flow outward at the AN’s is smaller than at the N’s, producing smaller flames there, as observed in the normal operating condition.

Experiments and discussion on the normal operating condition

The flame tube was constructed from a 5.75-ft length of galvanized downspout pipe of nominally circular cross section about 3 in. in diameter. One end was closed with a flat sheet of brass containing an inlet for gas from the laboratory valve, and the other end by an inexpensive loudspeaker. Along the top, 1/16-in. holes were drilled 1.5 in. apart. Two portholes were later cut in the side of the tube, one at a pressure N, and the other at an AN, corresponding to normal operation described below. The purpose of these was to accommodate the head of a sound level meter so that sound levels could be measured inside the tube (with the face replacing the missing part of the tube side). The gas flow to the tube was monitored by a flowmeter. A microphone was placed close to the outside of the tube at an AN to detect sound transmitted via wall vibration there, and its output was displayed on an oscilloscope. This facilitated tuning the tube to resonance and ensuring that the waveform was a clean sine wave.
Table I. Relative mass flows through holes of flame tube

<table>
<thead>
<tr>
<th></th>
<th>$p_e$ (N/m²)</th>
<th>$F_{\text{static}}$</th>
<th>Intensity (dB)</th>
<th>$p_m$ (N/m²)</th>
<th>$F_{\text{max}}$</th>
<th>$F_{\text{min}}$</th>
<th>$F_{\text{net}}$ (calc)</th>
<th>$F_{\text{net}}$ (exp)</th>
<th>$F_{\text{net}}^*$ (calc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sound off AN</td>
<td>0.9</td>
<td>1.0†</td>
<td>118</td>
<td>22.5</td>
<td>5.2</td>
<td>-4.8†</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>N</td>
<td>1.8</td>
<td></td>
<td>96</td>
<td>1.8</td>
<td>2.0</td>
<td>0.0</td>
<td>1.27</td>
<td>1.24</td>
<td>1.27</td>
</tr>
</tbody>
</table>

†All mass flow rates have been normalized to 1.0 for the flow with sound off.

††A negative mass flow corresponds to an inward flow of methane gas. This is possible because the pressure amplitude $p_m$ at the AN is about 22.5 N/m², compared to only about 1.8 N/m² for $p_e$ (the static pressure when the sound is on).

With our equipment, the optimum conditions for producing a good demonstration were found at 730 Hz with a gas flow of about 86 cm³/sec (a reading of 10 on the flowmeter). The sound pressure level readings inside the tube averaged to 118 dB at the AN and 96 dB at the N, corresponding to pressure maxima of 22.5 N/m² and 1.8 N/m², respectively. Outside the tube, at the gas outlet holes, the corresponding values were about 92 dB for all the AN's, while the N's ranged from 70-86 dB. (Standing waves in the room undoubtedly caused some of this variation.)

In order to determine whether the Bernoulli equation for gas flow out through the holes of the flame tube was valid over the range of pressures encountered in the tube, measurements of gauge pressure were made under various conditions. The pressure was measured using a U-tube manometer containing dibutyl phthalate ($\rho = 1.047$ g/cm³) connected through a 1/4-in. copper tube inserted into the side of the flame-tube at several points. These pressures were so low that it was necessary to tilt the manometer until it was almost horizontal in order to obtain appreciable readings. Under normal operating conditions with the sound off, the pressure was found to be about 0.9 ± 0.2 N/m². With half of the holes covered, the tube pressure increased by approximately a factor of four (while the total gas flow remained unchanged). This is the result predicted by the Bernoulli equation ($p_g \sim v^2$). Note that covering holes had no noticeable effect on flowmeter readings. The gas flow remained unchanged as a result of the fact that almost all of the resistance to flow was provided by the laboratory hand valve; this resulted in a constant-flow source, analogous to a constant-current generator.

Pressure measurements were also made for several flow rates covering the pressure range up to the maximum excess pressure encountered with sound on ($p_g + p_m$) at the AN. These data showed that for most flow rates the effect of viscosity is negligible; only at the highest pressures was there evidence of losses due to viscosity. For example, doubling the flow rate to statically reach $p_g + p_m$ at the AN increased the static pressure only slightly more (roughly 10%) than the theoretical multiple of 4.0. We concluded that for pressures well above those found at the N's, the Bernoulli equation is valid, and that it is a good approximation at the AN's when calculating mass flow rates through the holes.

When the sound was turned on, the measured gauge pressure $p_e$ immediately increased from about 0.9 to 1.8 N/m² at both N's and AN's. The reason for this is that the gas flow source is constant, and $p_g$ must increase to offset the impeding effect of the sound and thereby keep the average outward flow through the system of holes constant. This results in the flames at the N's being larger than they were with the sound off, while those at the AN's are smaller.

With these data it is possible to calculate theoretically the mass flow rate through the holes as the excess pressure $p_g + p_m \sin \omega t$ rises and falls at the N's and AN's. Substitution of the data corresponding to normal operation into Eq. (4), cast for simplicity into the form

$$F \sim \sqrt{p_g + p_m \sin \omega t}$$

(5)

yields the values shown in Table I.

The column headed $F_{\text{net}}^*$ (calc) lists the time-average net outward relative mass flows. These values were determined from plotted values of Eq. (5). It should be noted that $F_{\text{net}}$ (AN) < $F_{\text{static}}$ < $F_{\text{net}}$ (N), agreeing qualitatively with the observed flame sizes at normal operation. A re-calculation for the N's using $p_e = 0.9$ N/m² (the value observed with sound off) shows that $F_{\text{net}}$ (N) < $F_{\text{static}}$, corresponding to the initial impeding effect when the sound is first turned on, mentioned earlier.

In order to check our theory quantitatively, a measure of $F_{\text{net}}^*$ was required. Direct measurement of gas flow outward through individual holes was not possible, because the excess pressure inside the tube was too low. Flame height is not a good measure of mass flow, because the flames at AN's differ from those at N's both in diameter and in color. It was decided to use the heating effect of single flames as a measure of each $F_{\text{net}}$. Measurements were made of the time required to raise the temperature of 80 cm³ of water in an aluminum beaker through 20°C when placed over a single, isolated flame at an AN, at a N, and with sound off, for normal operation. Then the gas flow was varied with sound on, and heating effect measurements for a single flame taken as above until, by trial and
error, a flow rate was found that matched the heating effect for the AN and for the N. The relative mass flow rates obtained in this way, \( \bar{F}_{\text{net}} \text{(exp)} \), are listed in the next column of Table I. (Note that a simple average of the results for AN and N gives \((0.72 + 1.24)/2 = 0.98\), vs 1.0 for the static case, making the results seem reasonable in view of the constant flow input to the gas tube. There is more uncertainty related to the figure for the AN than for the N.) Comparing these rates with the calculated values of \( \bar{F}_{\text{net}} \) given in Table I, we see that for the N the agreement with theory is good.

**Refinements in the theory based upon further experiments**

A good reason for lack of agreement with theory at the AN is that the gas flow there differs from the flow at the N in that the flow reverses \(^5\) at the AN, while it is always outward at the N (for normal operation). If the incoming gas is at a higher temperature than the outgoing gas, less inward mass flow \( F_{\text{in}} \) (AN) occurs, and \( \bar{F}_{\text{net}} \) (AN) will be greater than the calculated value given in Table I. In order to refine the calculation of \( \bar{F}_{\text{net}} \), it was decided to measure temperatures near the outlet holes at normal operation.

For all flames, independent of flow rate, sound on or off, at N's or AN's, there is a dark nonburning layer of gas (and possibly air) at the base of the flame about 0.7 mm thick, which extends far upward within the flame, forming an almost cylindrical, hollow flame except at the top. This is especially true at the AN's. The temperature was measured with some difficulty within this dark layer of gas at different points using a copper-constantan thermocouple. In general, the temperature increased from bottom to top and from the hole outward, with about \( 280^\circ \text{C} \) for the top center of the dark layer. This was taken as a rough average for all the unburned gas drawn back into the hole. The temperature just beneath the holes was approximately \( 75^\circ \text{C} \) for sound on or off. Elsewhere within the tube the temperature ranged from \( 55-60^\circ \text{C} \) for equilibrium for normal operation. Recalculation of \( \bar{F}_{\text{net}} \) (AN) from Eq. (5) using the density corresponding to the observed temperatures on each side of a hole yields the theoretical relative mass flow listed in the last column of Table I under \( \bar{F}_{\text{net}}^\ast \) (calc). These rates compare favorably with the observed rates.

**Experiments and discussion on the reversal**

When the flow rate is decreased to about 1/3 the normal operation value (corresponding to \( p_g = 0.2 \text{ N/m}^2 \)) there is a transition to reversal operation; that is, as the flow rate is further reduced, the flames at the AN's become larger than those at the N's. Of course, all the flames are very small at such low flow rates. It was observed that for higher sound levels, reversal occurred at higher flow rates (higher \( p_g \)). We were unable to investigate this effect in detail because of distortion in our signal when the sound pressure level went beyond about 120 dB at the AN's. This reversal behavior is consistent with the observation by Rubens and Krigar-Menzel\(^5\) that as the sound intensity of their mechanical vibrator decayed, the flames changed from what we term “reversal” to what we term “normal operation.” Observations of the flames with a light chopper did not reveal any flicker under any operating conditions.\(^10\) It would be interesting to check for flicker at much lower frequencies, but we were unable to do this because our audio output was too weak at low frequency.

Our explanation for reversal is that with very low background pressure (or else high acoustic pressure), during the inward flow at an AN air and/or burned gas from the edge of the flame are drawn through the hole and partially dispersed throughout the tube. (Hereafter, this phenomenon will be referred to as “gulping.”) This results in a higher theoretical value for \( \bar{F}_{\text{net}} \) (AN). Whether such a process is possible can be checked by comparing the size of the flame with the displacement of the inward flowing unburned gas just outside a hole at the AN. This displacement, \( y \), is equal to \( \bar{v} \Delta r \), where \( \bar{v} \) is the average velocity of the ingoing gas and \( \Delta r \) is the time of inward flow (approximately one-half the period of oscillation).

The average velocity was determined graphically from a plot of Eq. (3), giving a value of \( y = 5.8 \text{ mm} \). The diameter of the flame base, at reversal operation, is about 3.0 mm at the AN and 7.5 mm at the N, while the hole diameter is about 1.6 mm. Thus the distance from the edge of a hole to the outer edge of the AN flame is considerably less than the 5.8 mm inward displacement. It seems reasonable, therefore, to assume that during inward flow both burned gas and air enter the tube at the AN, along with unburned gas.

During reversal there is also an inward flow at the N, but the calculated inward displacement there being only 1.5 mm vs a flame diameter of 2.5 mm, no gulping should occur at the N. Consequently, \( \bar{F}_{\text{net}} \) (AN) becomes larger than \( \bar{F}_{\text{net}} \) (N), resulting in larger flames at the AN.

An experiment was carried out to check for gulping. Cigarette smoke was trapped outside outlet holes and a laser beam shone down the axis of the tube through a small window at the end. With flames on, appreciable smoke was gulped through holes only at the AN; this occurred when gas flow was reduced to near that for a reversal. The gulped smoke particles were viewed through the (now Mylar-covered) portholes in the tube side as they dispersed far from the hole and scattered light from the laser beam inside the tube. We take this as evidence of air gulping.

At the transition from the normal operating condition to reversal, when the flames at the AN's are equal in height to those at the N's, it was observed that the smallest flames actually occur about midway between the AN's and the N's. This may also be explained on the basis of gulping. As one moves away from a N, one would expect the flame height to decrease if there is no gulping. But then as the AN is approached, the gulping effect rapidly increases and overpowers the above decrease.

The persistence of the flames at the AN's after the gas is turned off (with sound on) is a startling observation. Our first thought was that the flames at the AN's were due to acoustic pressure pumping out gas there while air is sucked in at the N's to keep the static pressure inside the tube at one atmosphere. To check this theory we taped up all the holes near the N's to prevent air intake there; the flames at the AN's still persisted for about three minutes. This persistence of the flames at the AN's with gas off can be explained by the gulping theory. Gas is pushed out during each positive half-cycle at the AN and gulping occurs during the negative half-cycle, resulting in a net mass flow out-
ward of unburned gas. At the node, meanwhile, with the gas turned off, the inward pressure amplitude is too low for gulping, and therefore $F_{\text{net}}$ (N) is too low for the flame to remain ignited. For sound off, it was found that to keep the flames ignited a flow rate of at least 0.25 that of normal operation was required. This appears to correlate with the observation described in reference 9.

The dramatic increase in air gulping when approaching reversal is hard to explain. One would expect a gulping effect to be present at the AN for the normal operating mode also. It would be reduced somewhat because the inward displacement is slightly smaller (5.3 mm) and the flame diameter larger than for reversal (about 4.5 mm). These differences may well be crucial, however, since the shortest path through the flame to the hole requires a 90° change in direction for the flowing gas, and at the calculated $V \approx 8$ m/s, such a flow path is improbable. This idea is supported by the observation that the flames at the AN’s were appreciably more slender than at the N’s for both normal operation and reversal; this suggests that the gas flow in and out at the AN’s tends to be mostly vertical.

We wish to acknowledge a number of helpful communications from R. Bauman on this subject and to thank A. Benade, T. Rossing, and the referee for suggestions made after reading our entire manuscript.

References

1. Al Bartlett brought this delayed flameout to our attention and especially emphasized that it occurred at the pressure AN’s, rather than at the N’s (where the flames were higher while operating normally, moments before). He and R. Bauman discussed this demo with us at the AAPT meeting in Rolla in June, 1976.

5. H. Rubens and O. Krigar-Menzel, Annalen der Physik 17, 149 (1905). We thank Robert Resnick for giving us this reference (which happens to be located next to Einstein’s initial relativity article) and for pointing out some of the difficulties he and Harry Meiners encountered when investigating this demo.

6. In a private communication, A. Benade informed us that this equation is incomplete. In addition to the Bernoulli pressure decrement, there is another quadratic term obtained from a Taylor expansion of the ideal gas law. The complete equation then becomes

$$\langle F \rangle = P_o + \frac{1}{B_o} \left( \frac{p_m}{2} \right)^2 \sin^2 \theta (\text{m}L) - \rho \left( \frac{u_o}{2} \right)^2 \sin^2 \theta (\text{m}L)$$

where $B_o$ is the bulk modulus. The quadratic terms here are equal in magnitude.

7. If $p_m > p_k$ in Eq. (3) and (4), the term $p_k + p_m \sin \theta$ becomes negative once each cycle; physically this means an inward gas flow through the hole occurs. To avoid mathematical difficulties in this situation we therefore used the absolute value of $p_k + p_m \sin \theta$ in calculating the magnitude of the flow, $F$.

8. These heating effect ratios were also measured by collecting the burned gases and hot air in a 34-lb. coffee can inverted over a single flame. The steady-state temperature reached near the highest point within the can adjacent to its wall was measured at the N, the AN, and with sound off. Static flows equivalent to those at the N and AN were found as before, resulting in almost identical results.

9. Using flowmeter tables, we found that the correspondence between heating effect and flow rates for static measurements was excellent over the range from $F_{\text{net}}$ (static) to $F_{\text{net}}$ (N) and fairly good over the range of low pressures from $F_{\text{net}}$ (AN) to $F_{\text{net}}$ (static).

10. R. Sutton, Demonstration Experiments. (McGraw-Hill, New York, 1938), p. 185, did observe a fluctuation in flame height at both N’s and AN’s.

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**questions students ask**

Send interesting questions to the editor.

**Why do you see the light?**

**Question:** Assume a monochromatic light source, such as a filtered incandescent bulb. If the radiation arises from random electronic transitions, the phase distribution should be random (e.g., as many as 45° as at 225°, relative to some arbitrary 0°). Why then is the net amplitude of the light not 0, since destructive interference should take place?

**This question was sent to us by Donald Maloney, physics teacher at Garden City High School, Garden City, New York 11530. It has been answered by Frank S. Crawford, professor of physics at the University of California, Berkeley, California 94720. Professor Crawford is the author of the text Waves, of the Berkeley Physics Course.**

**Answer:** The reason you see the light is that the intensity $I$ is not proportional to the electric field $E$ but to the square of the electric field. For a single light source we can write, in suitable units, intensity $I = E^2$. If $E$ is sinusoidally varying in time, its time average is zero (it is as often positive as negative); but of course the average of $E^2$ is not zero. Now suppose you have two light sources whose electric fields are superposed at the detector (say the retina of the eye); then the total electric field is $E = E_1 + E_2$ which averages to zero; but the total intensity $I$ is the average of $E^2 = E_1^2 + E_2^2 + 2E_1E_2$.

The “cross term,” $2E_1E_2$ does indeed average to zero, since, for any given value of $E_1$, $E_2$ is as likely to be negative as positive (assuming the sources are independent). Therefore $I$ is the sum of the average values of $E_1^2$ and $E_2^2$, which means it is the sum of $J_1$ (the intensity you would detect with source #1 alone) plus $J_2$ (the intensity for #2 alone). Thus, when you average over a long enough time, the intensity is just the sum of what you would get for the sources acting alone! If instead of averaging over a long time you could look at the intensity averaged over a short time like $10^9$ sec (for a typical gas discharge light source) then during some of those $10^9$ sec intervals you would get completely destructive interference, with the total intensity being zero: $(1-1)^2 = 0$. During other $10^9$ sec intervals you would get completely constructive interference with intensity being twice what you might expect if it were the sum of the independent intensities: $(1+1)^2 = 4 = twice (1^2 + 1^2)$. Over a long time the zero and 4 average to 2. If you look at all the other possible relative phases of the two sources you find that the total intensity is as often between 0 and 2 (partially destructive interference) as between 2 and 4 (partially constructive interference) and the average still comes out 2.